Gaseous Hydrogen and Muon Accelerators

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Muons, Inc. has formed partnerships with IIT, Fermilab, Jefferson Lab, and EM Design, LLC and obtained funding through the DOE SBIR/STTR program to develop techniques for muon beam cooling. Three funded projects are to develop
1) high-pressure high-gradient RF cavities,
2) cryogenic pulse compressors for high-power cavities, and
3) six-dimensional beam cooling using a helical dipole magnetic channel and continuous gaseous hydrogen absorber.

Muons, Inc. (est. 2002)

- July 2002
  - High-Pressure RF Cavities
    - STTR Ph I grant with IIT-DK ($100k/9mos)
- July 2003
  - High Pressure RF Cavities
    - STTR Ph II grant with IIT-DK ($500k/2yrs)
  - Cryogenic Pulse Compressors
    - Joint Venture with EM Design LLC
    - STTR Ph I grant with Fermilab-DF ($100k/9mos)
  - 6-d Helical Dipole Cooling Channel
    - SBIR Ph I grant with Jlab-YaD ($100k/9mos)

Need for Cooled Muon Beams

- Muon Colliders (Energy Frontier Machine)
  - Not limited by synchrotron radiation like e+e-
  - 1/10 energy and footprint of Proton Colliders
- Neutrino Factories (Muon Storage Ring)
  - Exciting New Physics
- Intense Sources of Muons
  - e.g. Muon Spin Resonance, muon catalyzed fusion

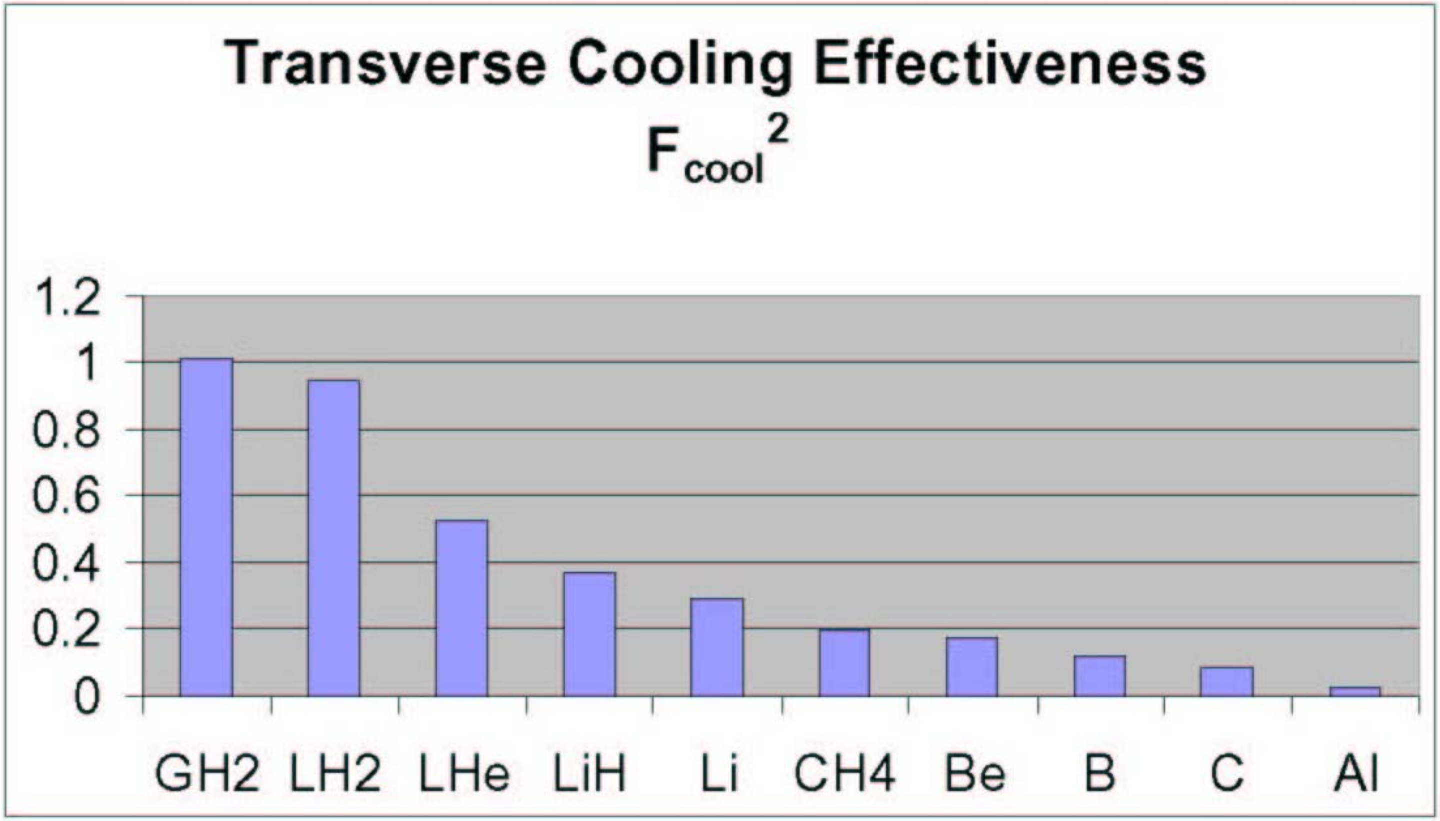
Muon Ionization Cooling

- Muons lose energy by dE/dx in 3 directions
- Longitudinal energy replaced by RF
- Focused by 5 Tesla solenoidal field
  – No Superconducting RF
- Cools to limit of multiple scattering

Hydrogen Gas Virtues/Problems

- Best ionization-cooling material
  - $(X_0 * dE/dx)^2$ is figure of merit
- Good breakdown suppression
- High heat capacity
  - Cools Beryllium RF windows
- Scares people
  - But much like CH_4

Comparison of Absorber Materials



Regions of Interest for High Pressure Gaseous Hydrogen Cooling Channels

	Pressure	Temperature	rho/rhoLH	dE/dx	L/200MeV	Vs	Rs/Rs293	Rs/Rs293
	Atm	K		MeV/m	m	MV/m	(@ 200MHz)	(@ 800MHz)
Gaseous H2								
at STP	1	293	0.001	0.04	5304	4	1.00	
Felici [1948]	**23**	293	0.027	0.87	231	**28**	1.00	
Lab G achieved	12	77	0.054	1.72	116	50		
Lab G goal	**100**	**77**	**0.450**	**14.35**	**14**	**435**	**0.35**	**0.35**
Liquid H2								
Averages Double Flip	1	293	0.125	3.98	50	50	1.00	1.00

HP HV RF Cavities

- Dense GH_2 suppresses high-voltage breakdown
  - Small MFP inhibits avalanches (**Paschen's Law**)
- Gas acts as an energy absorber
  - Needed for ionization cooling
- Only works for muons
  - No strong interaction scattering like protons
  - More massive than electrons so no showers

2002 STTR Phase I Project

To build an RF test cell for testing breakdown characteristics of gases for ionization cooling.

For use in Phase II for the exploration of Paschen's Law, relating breakdown voltages to gas density, over a range of temperatures, pressures, external magnetic fields, and ionizing particle radiation at Lab G and the Linac Test Area.

Gaseous Hydrogen for Muon Beam Cooling

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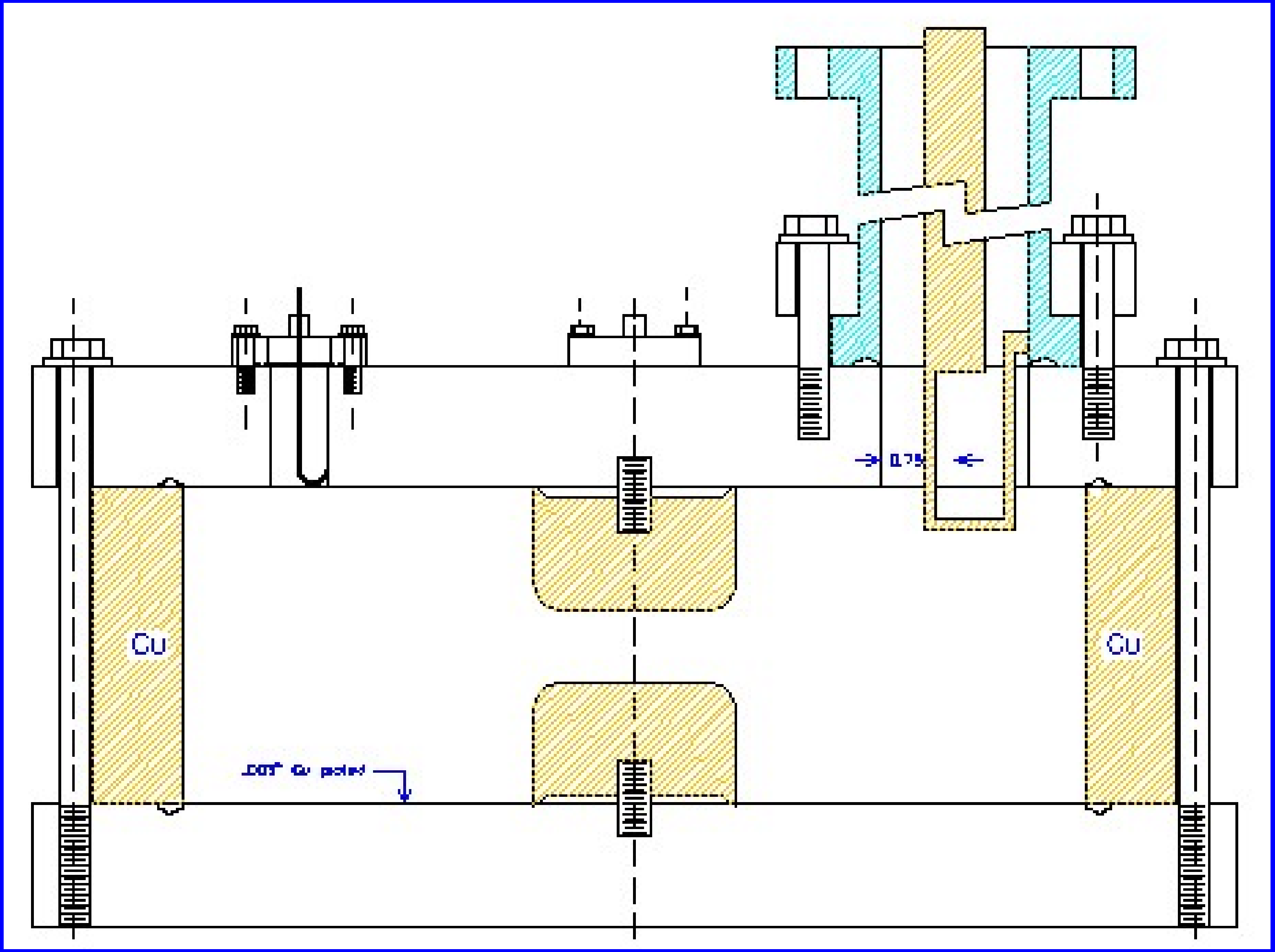
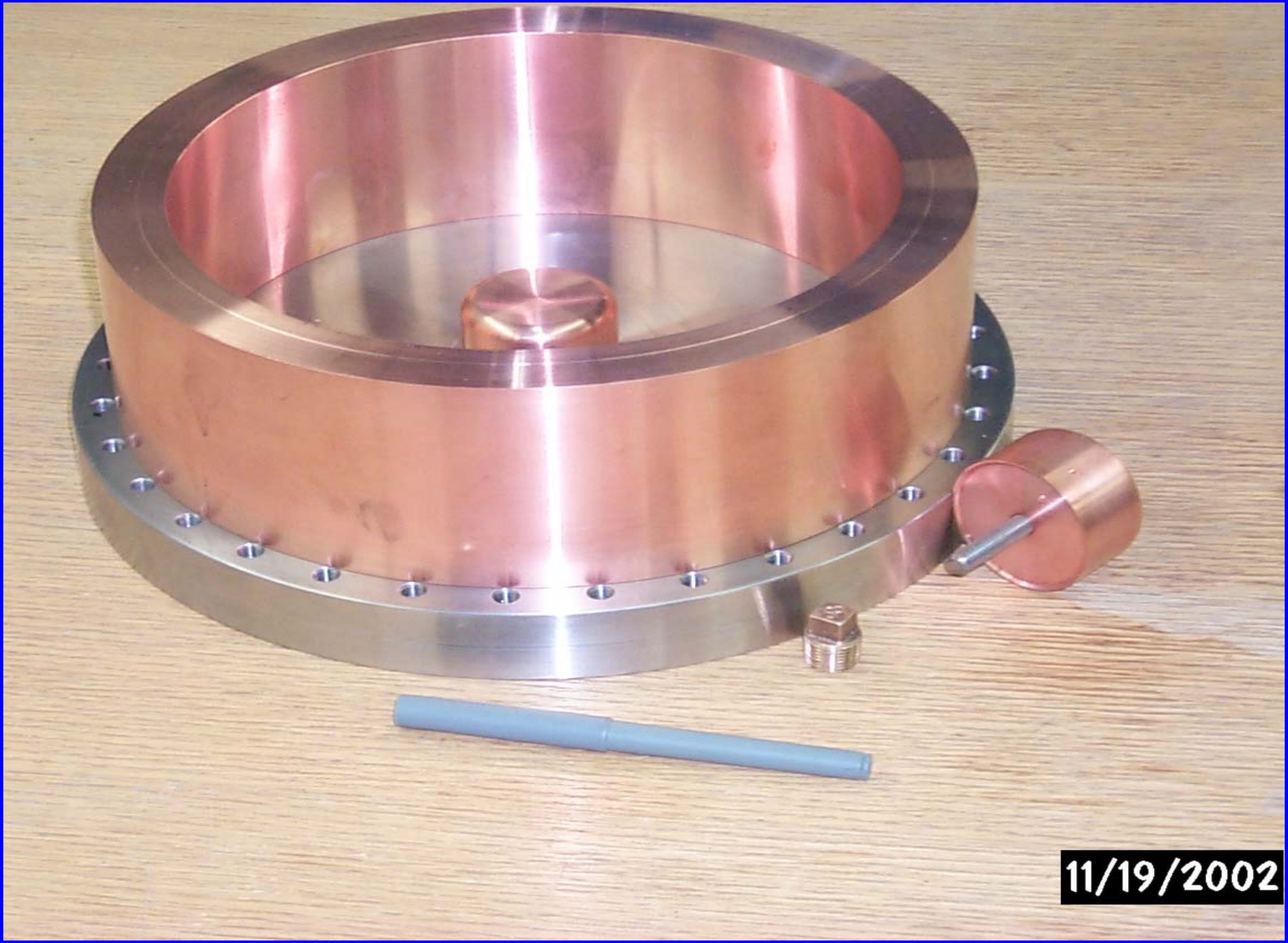
phase I results presented at PAC2003
Paper available at http://members.aol.com/muonsinc

805 MHz RF test cell schematic

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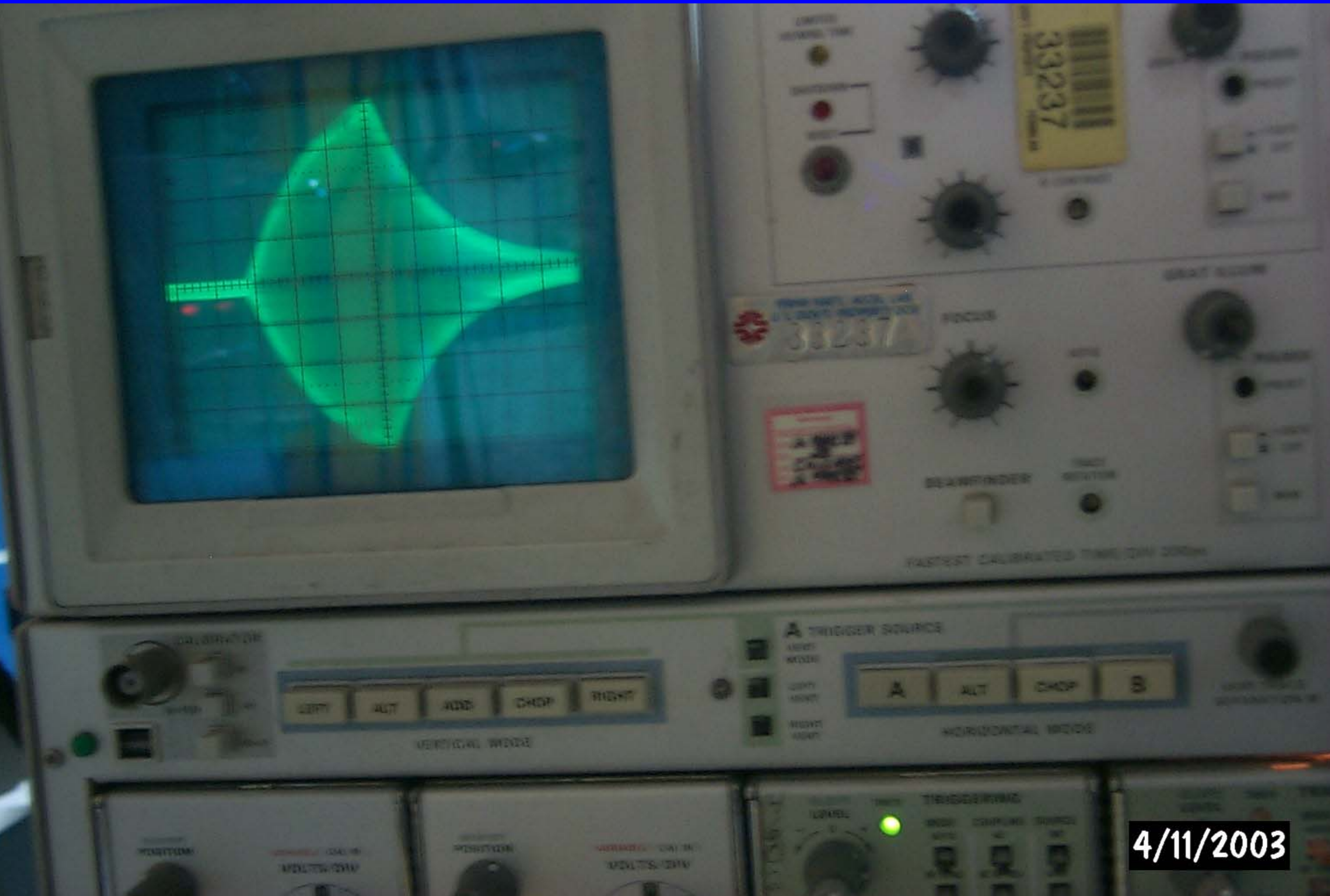
4/9/2003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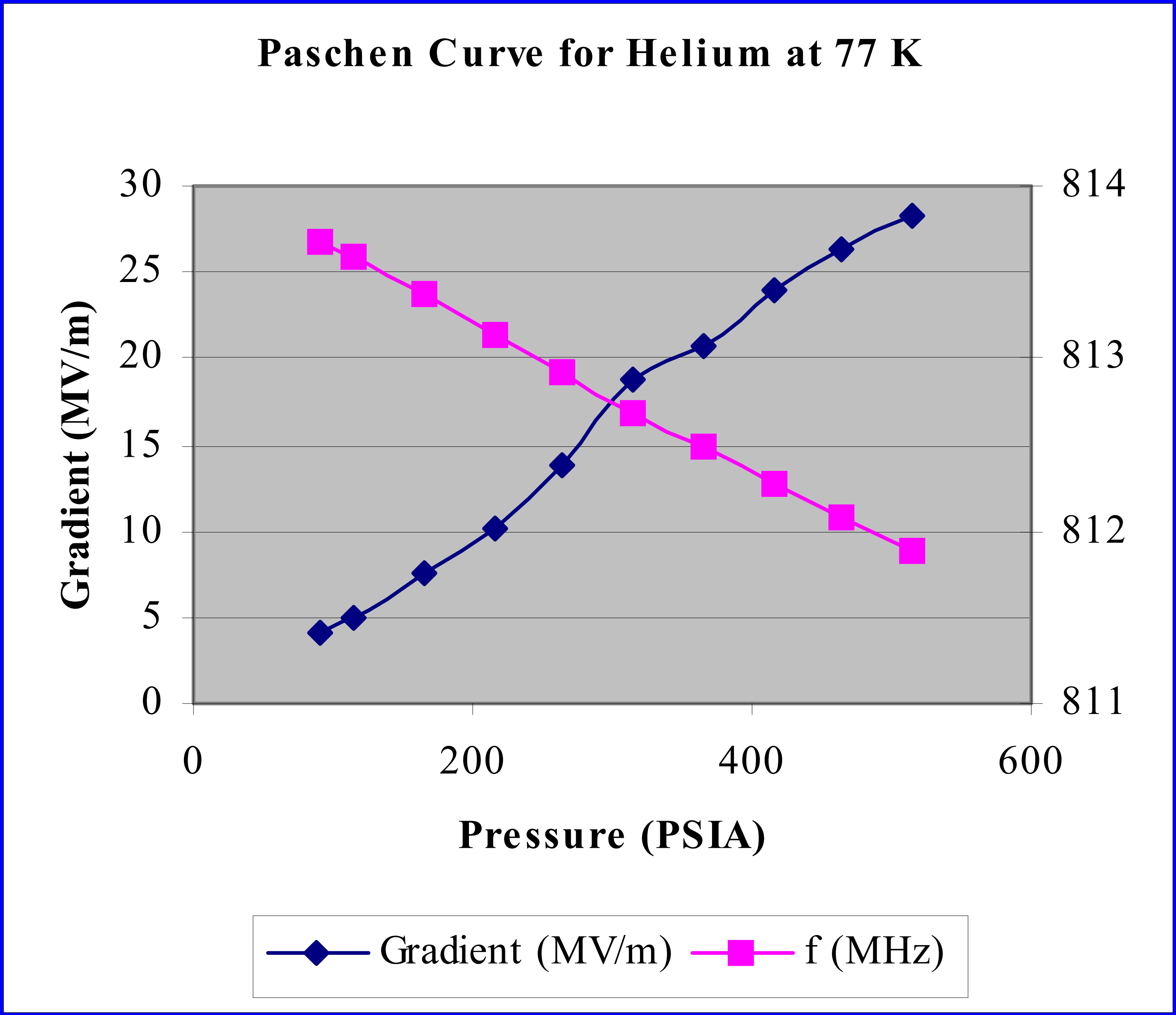
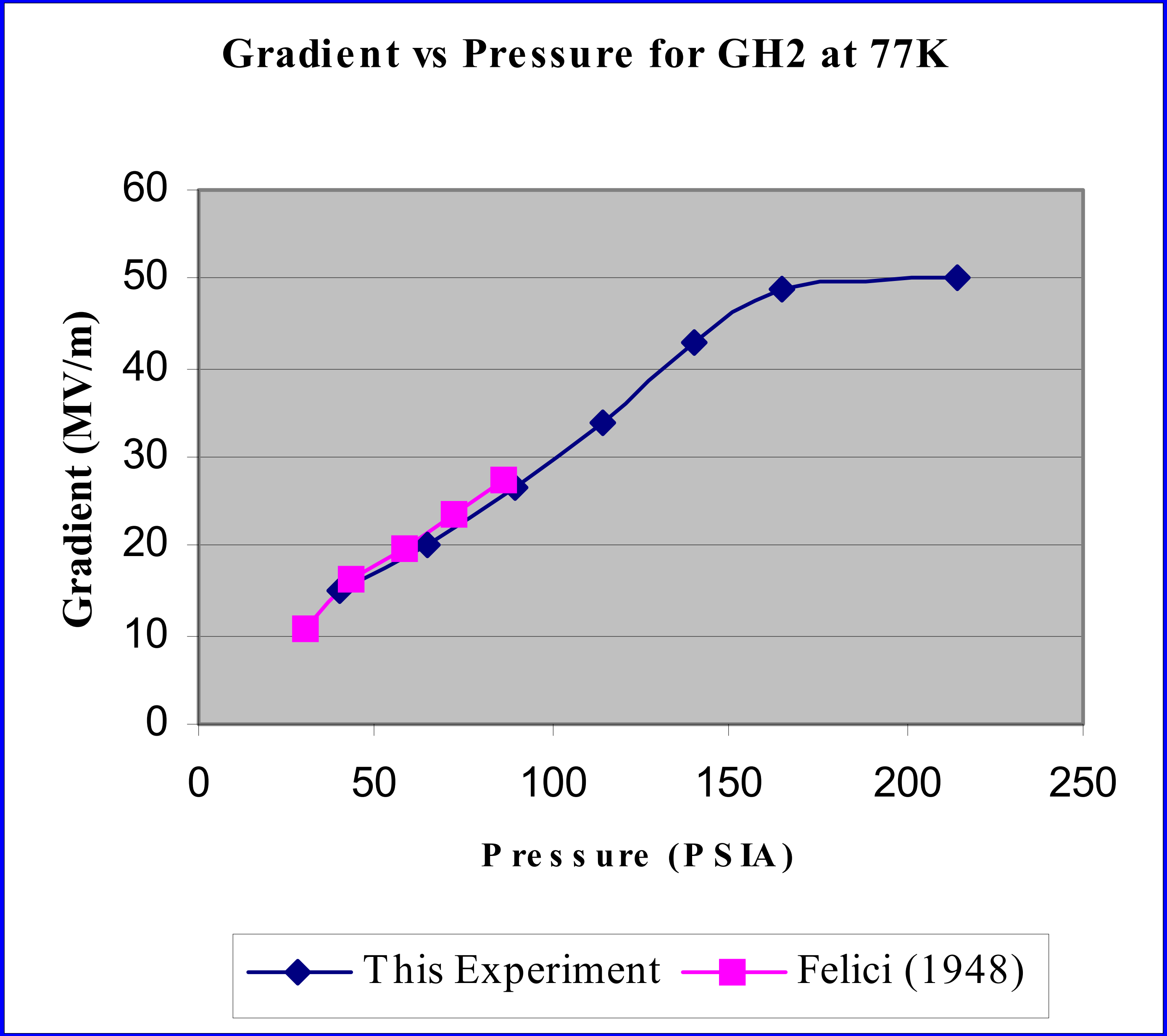
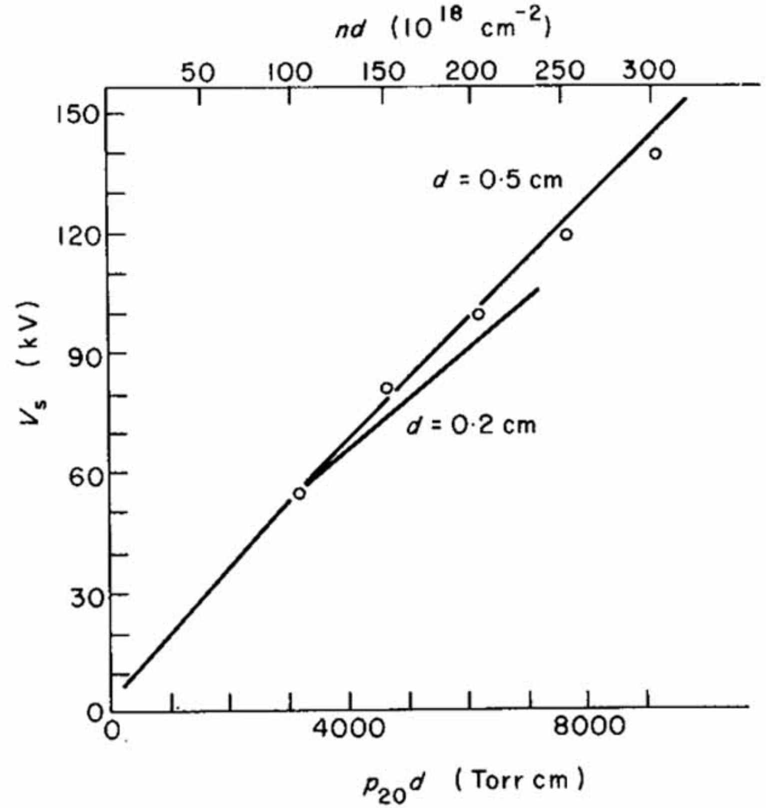


Paschen Curve for Helium at 77 K
30
25
20
15
10
5
0
814
813
812
811
0
200
400
600
Gradient (MV/m)
Pressure (PSIA)
Gradient (MV/m)
f (MHz)


Gradient vs Pressure for GH2 at 77K
60
50
40
30
20
10
0
Gradient (MV/m)
0
50
100
150
200
250
Pressure (PSIA)
This Experiment
Felici (1948)

H2 DC Paschen Data existed up to P=25 Atm,V=28 MV/m



Breakdown voltages in hydrogen (Müller, 1966. Reproduced by permission of Springer–Verlag)

—— Müller (1966)

○ Félici and Marchal (1948)


HOT
9/4/2002


10/11/2002


HANDLE WITH CARE
DELICATE INSTRUMENTS
FRAGILE
10/13/2002

STTR Phase I & II Status

- Measured helium Paschen curve
  - Built RF test Cell
  - Achieved Phase I goal
- Measured hydrogen Paschen curve
  - Satisfied FNAL safety requirements
  - 50 MV/m at 77 K and 12 Atmospheres!
- Phase II Granted 6/23/2003!!!!
  - Study Hydrogen breakdown (B and radiation)
  - Develop cavity designs (800 & 200 MHz)

Hopes for HP GH2 RF

- Higher gradients than with vacuum
- Less dependence on metallic surfaces
  - Dark currents, x-rays diminished
- Easier path to closed-cell design
  - Hydrogen cooling of Be windows
- Use for 6D cooling and acceleration
  - Homogeneous absorber concept

Present Activities for HP RF Phase II project

- Study breakdown with molybdenum and other electrodes
- Redesign Test Cell for Operation in the LBL 5 T solenoid
- Ensure MUCOOL Test Area Beam Line is available in 2005

2003 Muons Inc. Ph I Proposals:

- Transverse Ionization Cooling (w/ FNAL)
  - MANX ion-cooling demonstration (rejected)
- RF power sources (w/ FNAL)
  - Cryogenic pulse compressors (approved)
  - Joint Venture with EM Design LLC
  - MTA facility
- 6D Cooling (w/ TJNAF) (approved)
  - Homogeneous absorber (No wedges)
  - helical dipole channel

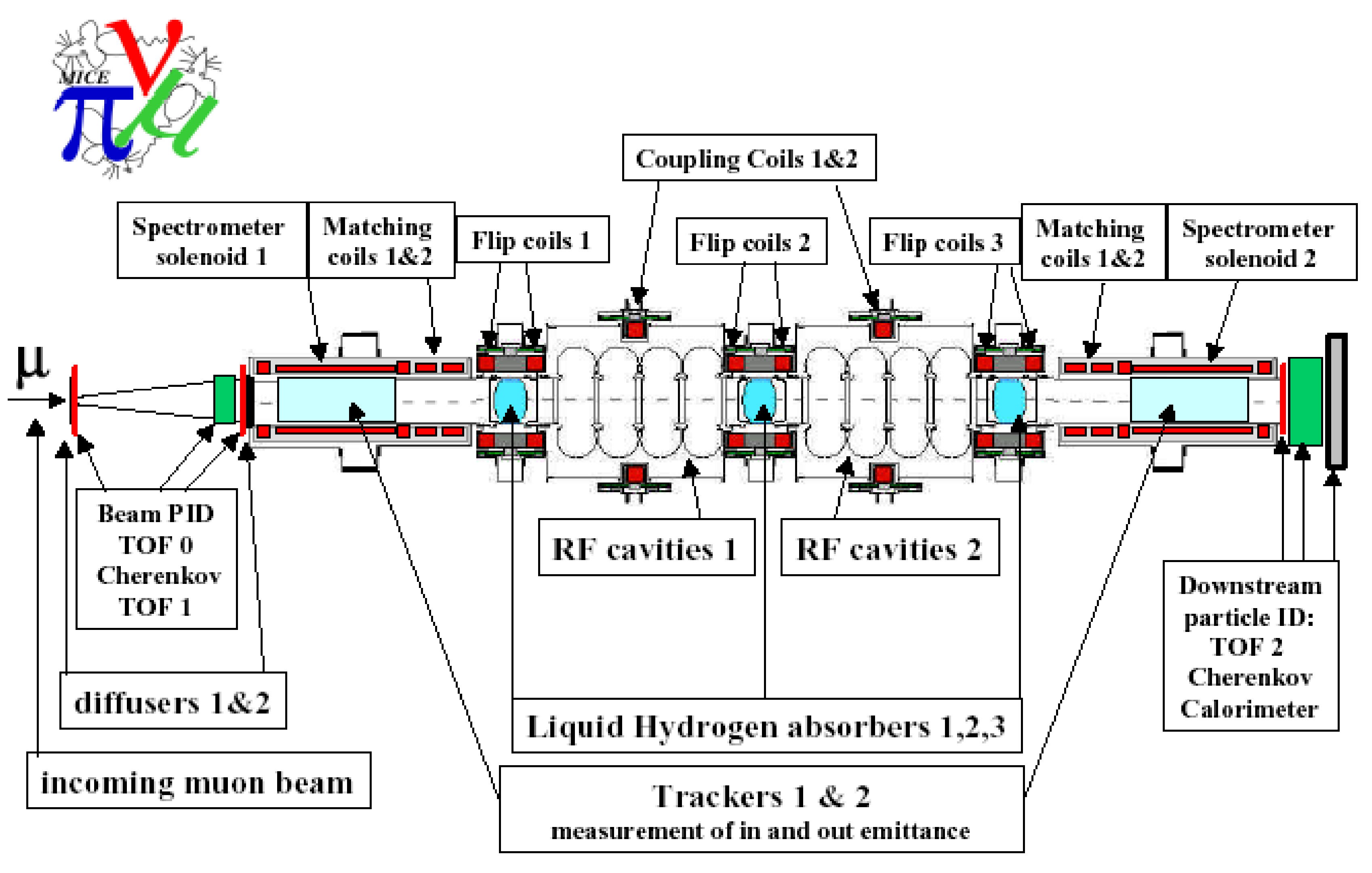
MANX MICE Comparison

- Conventional LH2 cooling channel
  - Liquid hydrogen absorbers between RF cavities
  - Placed at low β locations, where solenoidal fields change direction
- Proposed GH2 cooling channel
  - Continuous dense hydrogen absorber fills RF cavities
  - Low β is continuous along channel

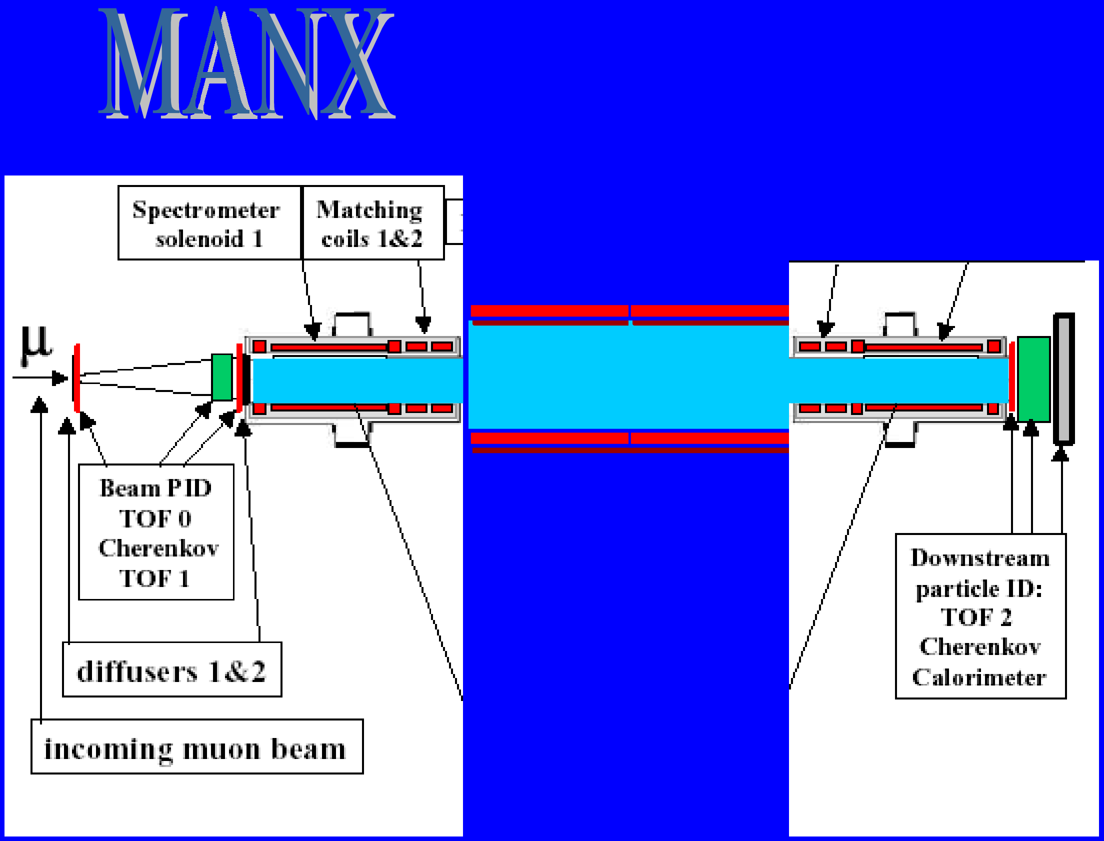
Muon Collider And Neutrino Factory eXperiment

- MANX follows MICE
- Hi-Pressure GH2
- Continuous Absorber
- Continuous low-β
  - Single-flip Solenoids
- Internal Scifi detectors
  - Minimal scattering

MICE


MICE
μ
Coupling Coils 1&2
Spectrometer solenoid 1
Matching coils 1&2
Flip coils 1
Flip coils 2
Flip coils 3
Matching coils 1&2
Spectrometer solenoid 2
Beam PID
TOF 0
Cherenkov
TOF 1
RF cavities 1
RF cavities 2
Downstream particle ID:
TOF 2
Cherenkov
Calorimeter
diffusers 1&2
Liquid Hydrogen absorbers 1,2,3
incoming muon beam
Trackers 1 & 2
measurement of in and out emittance

MANX is GH2 version of MICE



MICE changes into MANX

- Continuous GH2 replaces LH2 flasks
  - High density from P and/or T
- Opposing solenoids
  - Simple picture of "single-flip" lattice
  - Needs blackboard
- Detectors (scifi) in gas
  - No pressure windows to obscure cooling

Cryogenic Pulse Compressors

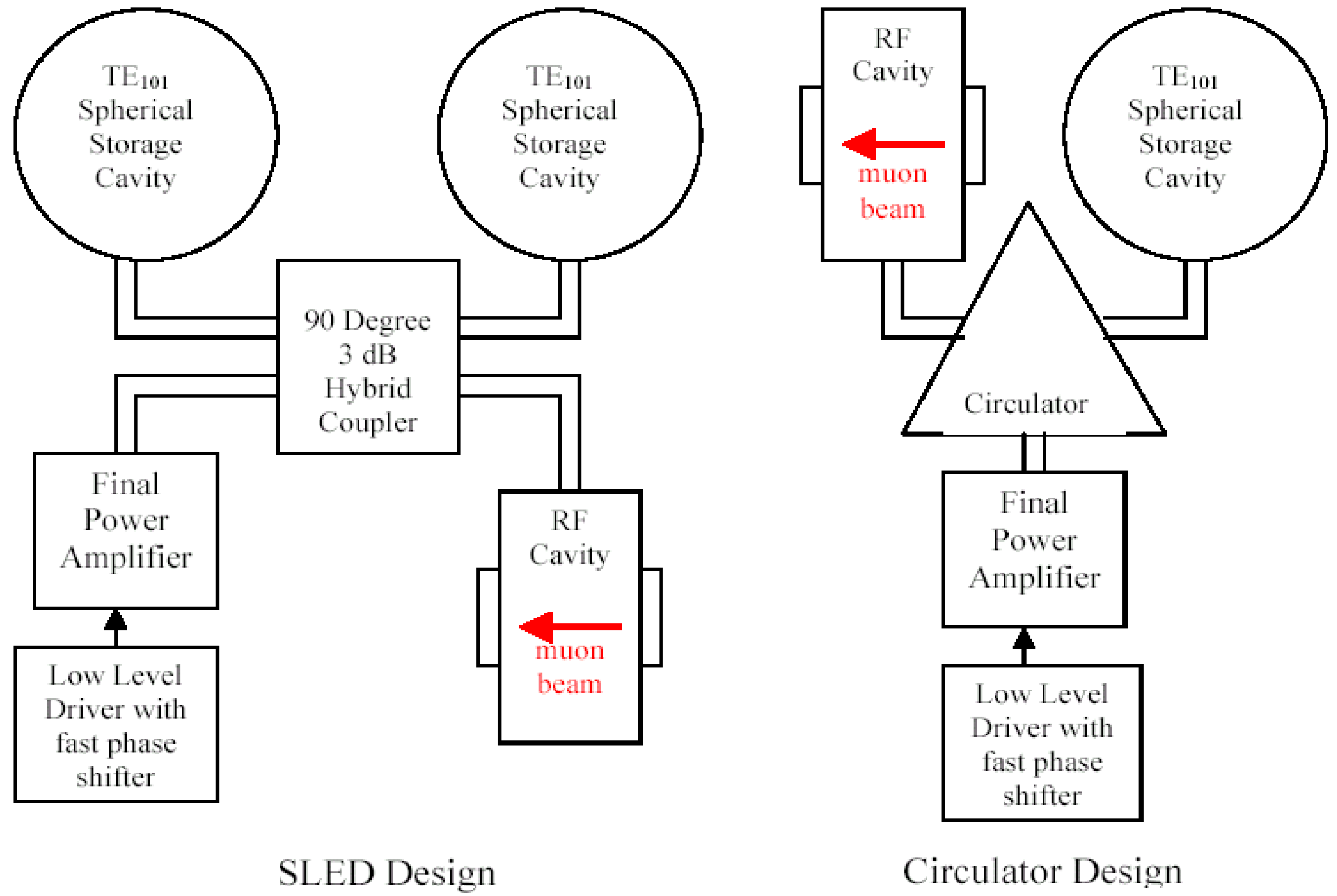


Figure 1. A comparison of the SLED and Circulator designs.

Magic of Pulse Compression

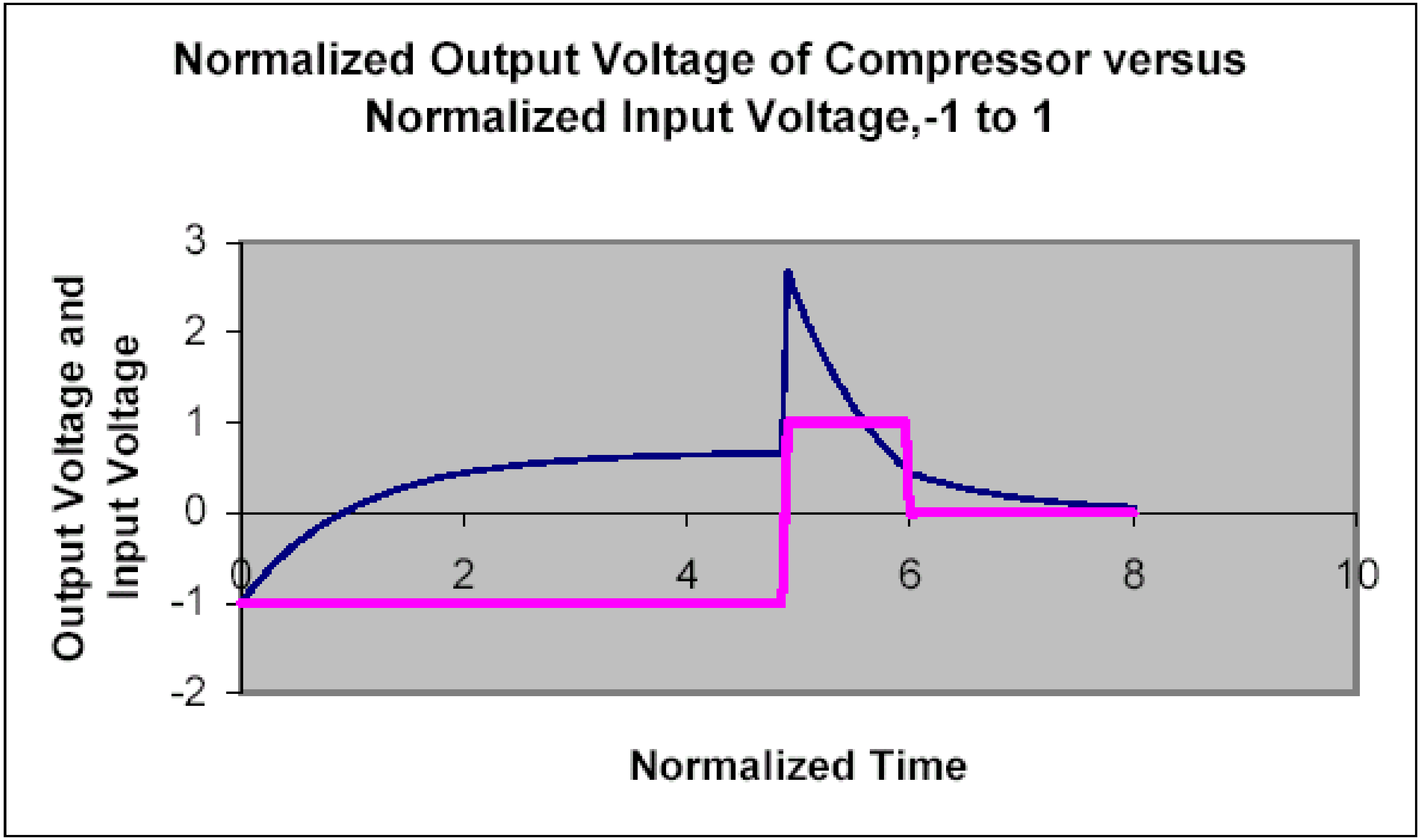
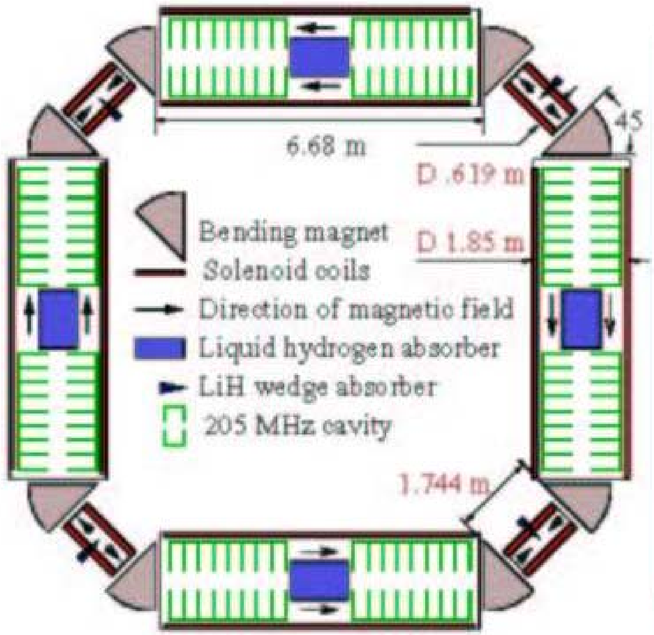


Figure 2. Input and output voltage of a compressor as a function of time.

6-dimensional cooling

- Essential for Muon Collider, useful for NF
- Still IC, but dE/dx depends on μ Energy
- Ring Cooler studies in fashion
  - Generates dispersion as in a synchrotron
  - Economical:15 turns means reused RF and absorbers
  - Problems with injection/extraction, absorber heating, RF beam loading

Balbekov Ring Cooler



Circumference	36.963 m
Nominal energy at short SS and bends	250 MeV
Bending field	1.453 T
Norm. field gradient	0.5
Max. solenoid field	5.155 T
RF frequency	205.69 MHz
Accelerating gradient	15 MeV/m
LH_2 absorber length	128 cm
LiH wedge absorber	14 cm
Grad. of energy loss	0.75 MeV/cm

Figure 1: Layout and parameters of the solenoid based ring cooler.

Emittance Exchange With GH2

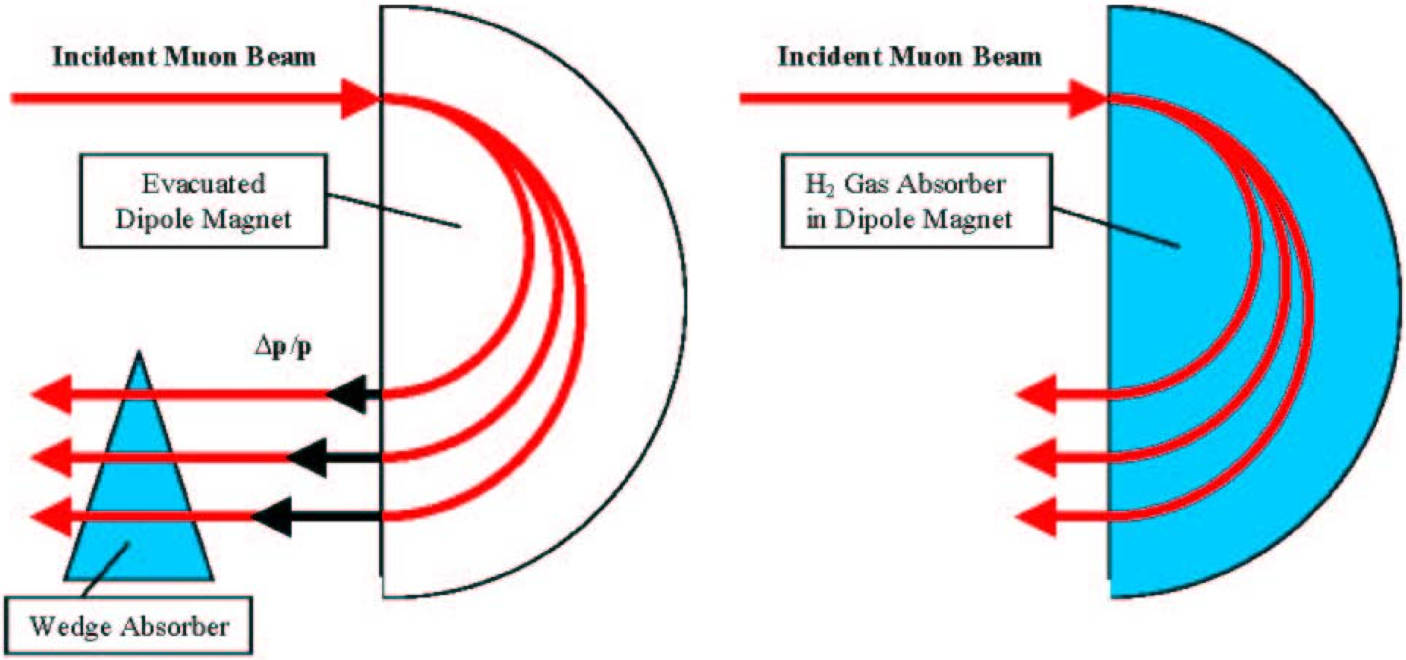


Figure 1. Use of a Wedge Absorber for Emittance Exchange

Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

6-d Cooling with GH2

- Derbenev channel: Solenoid plus transverse helical dipole fields
- Analytically see equal cooling decrements and 10^6 phase space reduction in ~150 m channel
- Avoids ring problems
  - Injection and Extraction simpler
  - No Multi-pass Beam loading or Absorber heating
  - Can adjust channel parameters as beam cools

Six-dimensional muon beam cooling in a continuous, homogeneous, gaseous hydrogen absorber

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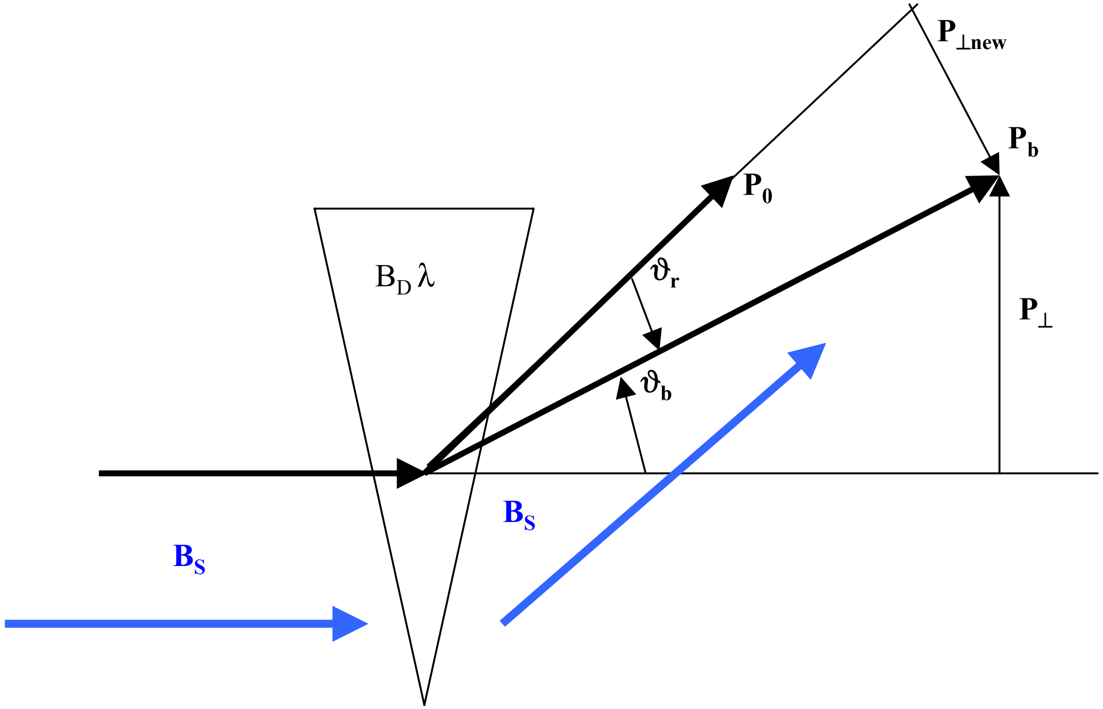
Paper contributed to COOL03 Meeting Hotel Fuji, Japan

http://members.aol.com/muonsinc/COOL03_6-d_rev1.pdf

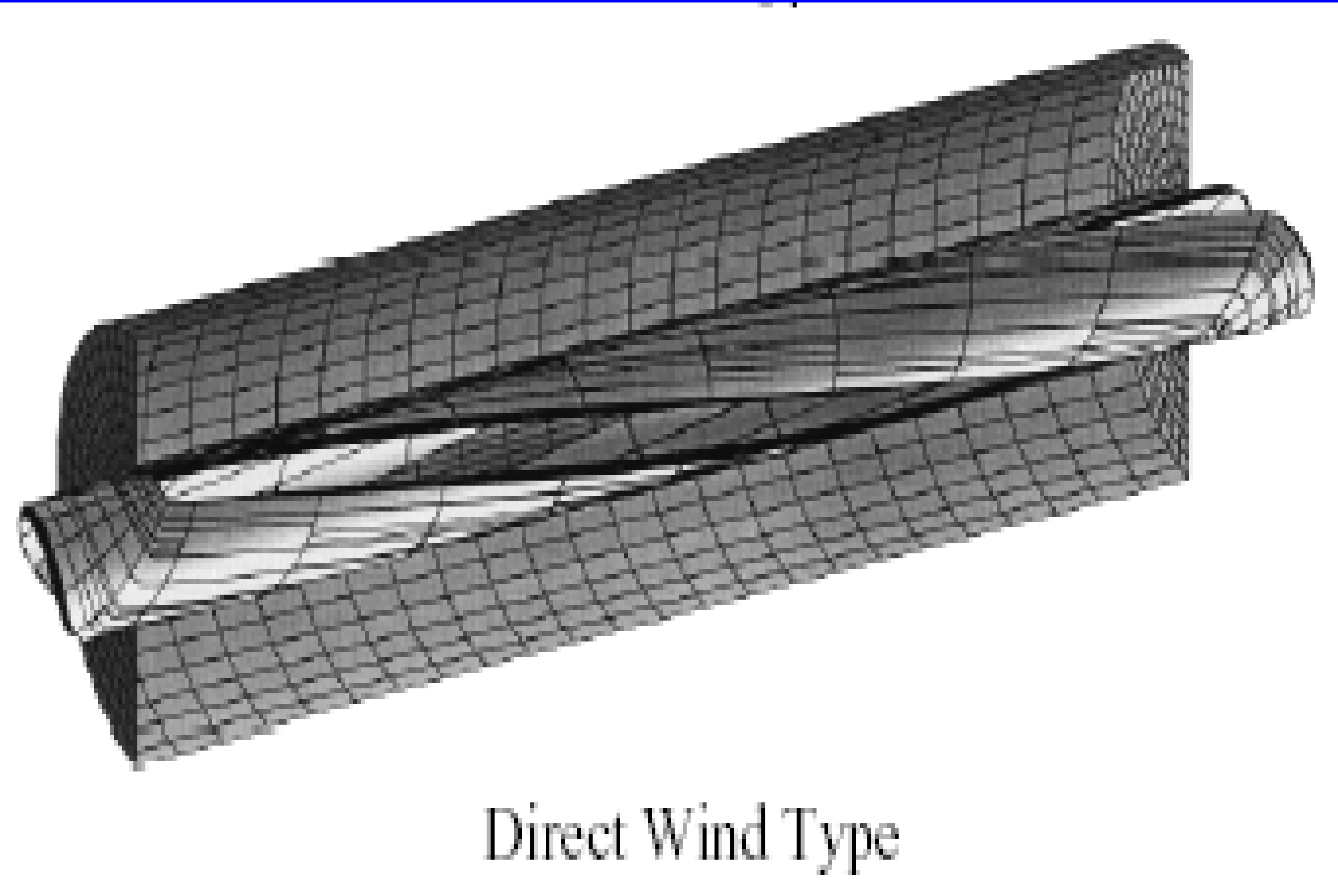
Dipole on a Bent Solenoid



$$P_{\perp new} = P_b\vartheta_r = P_b\,(\vartheta_0 - \vartheta_b) = P_b\,((P_b\,\vartheta_b / P_0) - \vartheta_b) = P_b\,\vartheta_b\,((P_b - P_0)/P_0) = 30\,B_D\,\lambda\,(\Delta P/P).$$

$$P_{\perp new} = P_b\vartheta_r = 30\,B_S\,\rho_{S,} \quad \text{or} \quad \rho_S = (\lambda B_D/B_S)(\Delta P/P)$$

Helical Dipole Magnet (c.f. Erich Willen at BNL)



Transverse Field Harmonics

the rate the dipole is twisted in turns/m and we **define $k = 2\pi$ turns/m**

$$B_\varphi \propto \cos \ell(\varphi - kz),\ \ell = 1, 2, 3, 4....,$$

$$B_\rho \propto \sin \ell(\varphi - kz)$$

$$B_Z = -k\rho B_\varphi$$

$$x + iy = \rho e^{i(\varphi - kz)}$$

Periodic Orbit Solution

$$\kappa = \left[\frac{p_\perp}{p_Z} \right] = ka = \frac{1+\kappa^2}{k - k_C} \frac{B_\varphi}{p_Z}$$

where $e = c = 1$,

$$k_C = B_S / p_Z$$

$$p / p_Z = \sqrt{1+\kappa^2}$$

Periodic Orbit momentum versus radius

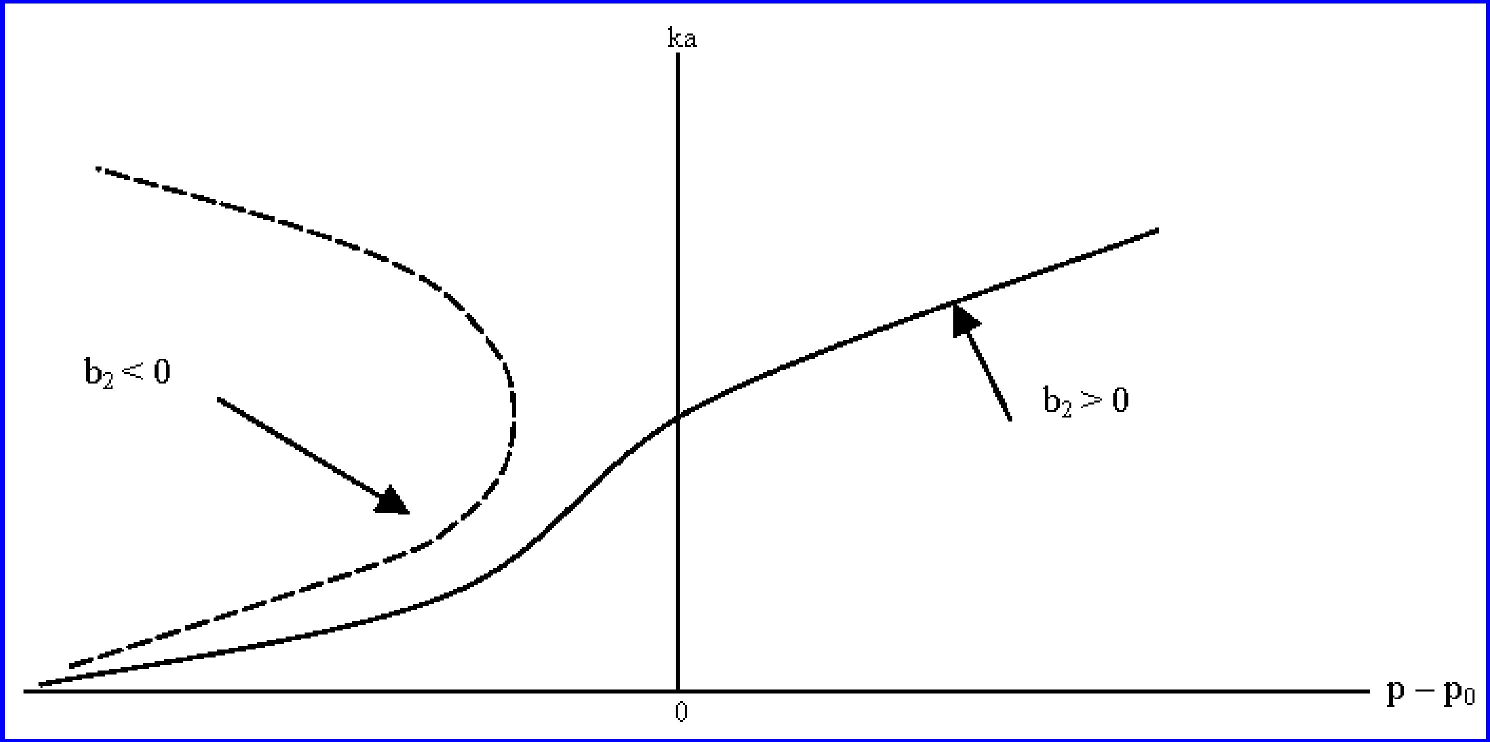
In this paper the helical magnet system is composed of dipole, quadrupole, and octupole components. It is convenient then to rewrite the previous equation in the following form:

$$p - p_0 = \frac{-b_1}{\kappa} + \frac{1}{2} b_2 \kappa^2$$

Where p_0 is determined by:

$$k\, p_0 = B_S + \frac{1}{k} \frac{\partial B_\varphi}{\partial x},\ at\,(x, y) = 0$$

Regions of Stability



Dispersion

$$\hat{D} = \frac{da}{a} \Big/ \frac{dp}{p} \approx p \Big/ \left[\frac{b_1}{\kappa} + b_2 \kappa^2 \right]$$

Translational Mobility, η

$$\eta = \frac{d}{d\gamma}\frac{1}{\beta_Z} = \frac{\sqrt{1+\kappa^2}}{\gamma\beta^3}\left(\frac{1}{\gamma_{tr}^2} - \frac{1}{\gamma^2}\right)$$

, where

$$\gamma_{tr}^2 \equiv \frac{1+\kappa^2}{\kappa^2}\hat{D}^{-1}$$

Cooling Decrements

$$\Lambda_6 = \Lambda_\gamma + \Lambda_2 + \Lambda_3 = 2\left(\frac{dE}{dz}\right) / \gamma mc^2$$

$$\Lambda_\gamma = \frac{dE / dz}{\gamma\, mc^2 \beta^2}\left[-\frac{2}{\gamma^2} + \hat{D}\frac{\kappa^2}{1+\kappa^2}\right]$$

Equal Decrements

Equating the three decrements leads to two conditions:

$$\hat{D} = \frac{2\left(1+\kappa^2\right)}{\kappa^2}\left(1-\frac{2}{3}\beta^2\right)$$

and, as follows from formulae for transverse decrements in reference [9],

$$\frac{k_C}{k} = 1 + \sqrt{\frac{\beta^2}{3-\beta^2}\left(1+\kappa^2\right)}$$

Translational Mobility for Equal Decrements:

$$\eta = \frac{\sqrt{1+\kappa^2}}{\gamma\beta^3}\left(1 - \frac{1}{3}\beta^2\right)$$

Helical dipole cooling channel parameters

Parameter	Unit	Initial	Final
<Beam momentum, p>	MeV/c	300	100
Solenoid field, BS	T	6	16
<Cyclotron wavelength>	m	1.09	
Helix wavelength	m	2.00	0.25
Maximum momentum	MeV/c	345	
Minimum momentum	MeV/c	255	
Momentum spread	%	30 (total)	2 (rms)
Orbit radius at p max	cm	20	
Orbit radius at p average	cm	16	2
Orbit radius at p min	cm	8	
Orbit width due to momentum spread	cm	12	0.28 (rms)
Beta-functions	cm	45	5.3
Transverse emittances, each plane, normalized	cm x rad	1	2.8 10-2
Orbit spread due to emittance	cm	3.5	0.4
Translational mobility		0.25	2
Helical magnet inner radius	cm	30	5
Transverse field at magnet	T	2	6

At 110 Atm, 77 K

The total energy loss in this calculation is 2.4 GeV. For a channel of continuous dense hydrogen gas with 14 MeV/m of dE/ds, this implies a channel length,

$$L = \frac{2.4}{0.014\sqrt{1+\kappa^2}} \approx 150\ m$$

Conclusions

- GH2 an enabling technology for μ machines
  - Shorter, less-expensive, more efficient cooling
  - Less expensive acceleration for Neutrino Factory
  - 6-d Cooling makes Muon Collider possible
- SBIR/STTR funding new for basic research
  - Explicit in last solicitation
  - Muons, Inc. and IIT have new
  - Postdoc Dr. Katsuya Yonehara
  - Scientist/engineer Dr. Moyses Kuchnir